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From pesticides to genetically modified plants: history, economics and politics

J.C. ZADOKS[1*] AND H. WAIBEL[2]

[1] Laboratory of Phytopathology, Wageningen Agricultural University, P.O.Box 8025, NL-6700 EE Wageningen, The Netherlands
[2] Department of Horticultural Economics, University of Hannover, Herrenhäuserstrasse 2, D-30419 Hannover, Germany
[*] Corresponding author (e-mail: jczadoks@euronet.nl)

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Abstract

Two technologies of crop protection are compared, crop protection by pesticides and by Genetically Modified Plants (GMPs). The history of pesticides provides lessons relevant to the future of GMPs; (1) high pesticide usage is counter-productive, (2) the technology requires intensive regulation and (3) has nonetheless many external effects which strongly reduce its social benefits, (4) early calculations on net benefits of pesticides were over-optimistic, and (5) intensive use of pesticides made farmers so dependent on them that they lost important options. These lessons are used to construct a framework for the economic analysis of GMPs which can be applied once sufficient empirical information becomes available. Conceptually the framework can be used for a comparison of crop protection strategies indicated as chemical crop protection, threshold-based crop protection, crop protection by ecotechnology and organic agriculture. Given the current state of knowledge on the impact of GMPs where (1) benefits are assumed rather than proven, (2) regulatory costs are rising and (3) environmental and human health risks have yet to be fully identified, one conclusion is that *ex ante* economic analysis which draws upon some of the lessons learned with chemical pesticides may help to bridge the gap between the proponents and the opponents of GMT (Genetic Modification Technology).

Keywords: Crop protection, economic analysis, genetic modification, new technology in agriculture, pesticides, welfare theory.

Introduction

Modern crop protection (Figure 1) remains in the forefront of the public debate. While the discussion on the risks, the general necessity and the economically optimal levels of synthetic pesticide use has not come to an end, today genetically modified plants (GMPs) raise concerns in many parts of civil society, especially in Europe.

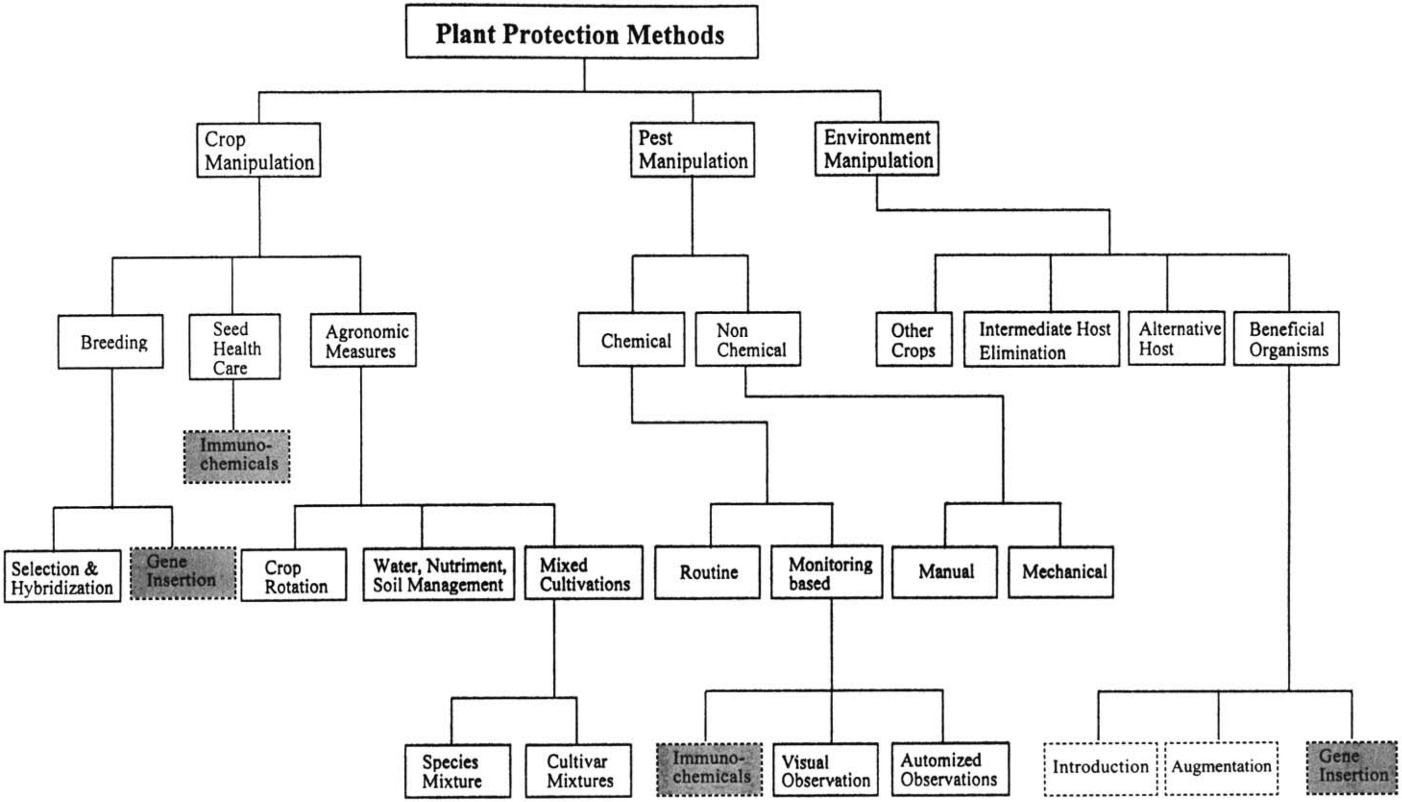

Figure 1. A classification of plant protection methods. Crop protection relies on the manipulation of either crop, pest or environment by various methods including conventional technology (drawn lines), traditional biocontrol technology (broken lines) and genetic modification technology (gray).

When organic pesticides were introduced some fifty years ago great expectations were raised. The enthusiasm among scientists was rendered (Kommedahl, 1981), not without some irony:

> *'A bright new star, a nova, named DDT had just burst brilliantly into the plant protection heavens. It was accompanied by some bright satellites; the dithiocarbamates for plant disease control, 2,4D for weed control and DD for nematodes. Crop plants have never been so free of pests since agriculture was established. In the leaf hopper areas of America, potatoes have never been so green in September. The yields were doubled, often quadrupled'.*

While there have been similar, highly optimistic statements on GMPs initially, crop protection scientists generally have become more realistic in their expectations. However, even The Economist (February 20, 1999) warned not to slow down the development of genetically modified plants in response to public panic about perceived health risks, pointing to their economic benefits to agriculture.

There are obvious parallels between the 'pesticide revolution' and the 'GMP-revolution' in crop protection. Both technologies were rapidly introduced by multinational companies, quickly dominated the scientific debate and reached high adoption rates among farmers. While negative externalities of pesticide use soon became subject to serious criticism, mainly stimulated by the publication of Carson's *Silent Spring* in 1962 and by the assessment of Pimentel *et al.* (1980, 1993), GMPs are seen by their promoters as the safest way to escape the pesticide treadmill and as a necessity to overcome the world's food problem. Similarly, for a long time the economic benefits of pesticides were undisputed due to their overall comfortable rate of return of about 4:1 (Headley, 1968). However, this value became challenged recently because of methodological flaws in benefit assessment (Lichtenberg & Zilberman, 1986) and empirical evidence from Germany (Waibel & Fleischer, 1998) suggesting that, from an economic point of view, pesticides are overused. Similar findings are not yet available for GMPs mainly because of a lack of empirical data.

The present paper compares the rise and expected reduction of synthetic pesticides with the expected rapid diffusion of GMPs in agriculture. It is argued that there are lessons from the 'pesticide story' that can help to reduce the costs of the GMP technology so that it more effectively contributes to the goals of society. Unfortunately these lessons are ignored by those crop protection scientists who risk to escape the 'pesticide treadmill' by jumping onto the bandwagon of genetic engineering as the major technology of crop protection in the 21st century. A plant pathologist and an agricultural economist joined to show recent trends in pesticide-based crop protection and in GMPs, identify commonalities and differences, and outline a framework of economic assessment that takes into account the needs of society at large in the context of welfare economics.

It is well recognized that a comparison between two technologies that were introduced during two different periods of time, between which rather significant social changes took place, must be handled with care. For example, when pesticides were introduced the public met new technology with an optimism characteristic for the period of economic growth following World War II. At the turn of the century, the general public, especially in Western Europe, tends to distrust the judgement and independence of scientists (Paillotin & Rousset, 1999). Despite of these methodological shortcomings, a comparison between the application of pesticides and GMPs in crop protection is considered to be useful, not only because of the similarity in many of the effects on productivity and possibly on environment but especially because conclusions can be drawn on how the analytical framework must be adjusted in response to the social changes affecting science and technology.

Lessons learned from synthetic pesticides

When synthetic pesticides were introduced some fifty years ago, great enthusiasm existed about their ability to sustainably solve the world's food and productivity problems. Meanwhile, concerns about their negative side-effects to humans and the environment often dominate the debate. Five major lessons can be learned from synthetic pesticides which relate to the introduction of GMPs in agriculture.

Lesson 1

The first lesson from the 'pesticide story' is that, in spite of the sophisticated regulatory framework, there continue to exist external effects, i.e. costs which are borne neither by producers nor by the users of pesticides but which society has to pay. It became obvious that there are two kinds of external effects. First, off-site external effects appear such as water pollution by pesticides costing at least some 130 million DM per year in Germany (Waibel & Fleischer, 1998). Second, external effects of an intertemporal and even intergenerational nature are noted. An example are eventual carcinogenic and teratogenic effects of pesticides and their metabolites. These are particularly difficult to quantify because existing tests are inadequate to allow proper conclusions.

Theoretically, external effects of a technology (Pearce & Tinch, 1998) are related to its scale (Figure 2) and to complementary relationships among technologies. As a technology spreads because of its comparative advantage, the risk of generating external effects will increase. A good example for scale effects of externalities by technology diffusion is the spread of the rice variety IR 36 in Asia. Its hectareage increased rapidly and so did the selection pressure for new biotypes of the brown plant hopper. Continuous pesticide use effectively reduced populations of natural enemies and thus facilitated the appearance of new biotypes which overcame varietal resistance (Kenmore, 1996). Intensivation of rice cropping resulted in higher pesticide use and at the same time reduced the refuge potential of the environment for natural enemies previously acting as a stabilising force in the ecosystem. Hence, the short-term economic advantage of pesticides creates costs even to the non-users of the pesticide technology because of increasing scale and increasing technology interaction.

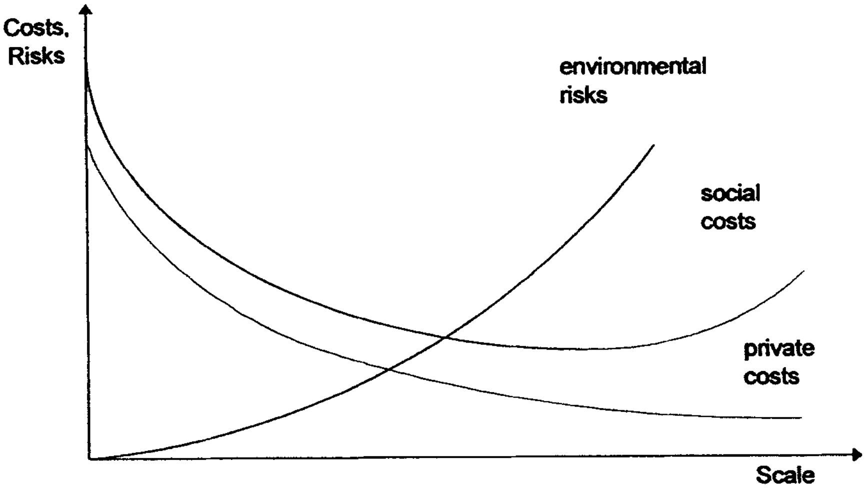

Figure 2. Scale effects of technology adoption. When an agricultural technology becomes widely adopted its private costs decrease because of economies of scale while its environmental risks (e.g. development of new pest biotypes, resistance of pests against toxic compounds, water pollution) increase. As a net result the social costs may decrease at the beginning but later they tend to increase with scale.

Lesson 2

The second lesson from the pesticides story is that, as their external effects became recognised, governments responded with more regulation. More regulation usually means stricter requirements for the registration of new chemical products resulting in higher development costs. The development costs of an active ingredient now is claimed to reach the order of 150 million Euro or US$ per compound. The economic implication of this process is that for firms producing pesticides the investment costs increase relative to the production costs of the chemical materials. Hence producers aim at large production volumes in order to lower their average costs. Large volumes require companies to increase their market share of a given product rather than searching for niche markets. Hence, the number of available components is reduced and thus the number of pest control options. This can be detrimental to the implementation of Integrated Pest Management (IPM) especially in crops with minor pesticide markets.

Lesson 3

The third lesson is that benefits of pesticides have been overestimated because of the wrong reference system used. The influential study of Headley (1968), which established the 'standard benefit cost ratio' of pesticides at 4:1, treated pesticide inputs in a production function framework. This implied that pesticides are ordinary yield increasing factors. Consequently, depending on the functional form used, the method leads to a significant overestimation of the productivity effects of pesticides. The methodological flaws underlying this approach were first shown by Lichtenberg & Zilberman (1986) who incorporated the damage abatement nature of pesticides into the production function. Recent economic studies showed that the benefits from pesticides are much lower than previously assumed. Rola & Pingali (1993) found that insecticide use in rice on average is uneconomical. Pimentel *et al.* (1993) calculated for US agriculture a benefit cost ratio of 1.3 only, while Waibel & Fleischer (1998) found that the benefit cost ratio for aggregated pesticide use in Western Germany (before unification) was 1.5 although conservative estimates of the external costs were made. Babcock *et al.* (1992) found for fungicides in apples that the marginal product may have been overestimated by a factor of ten if estimates ignore the damage function. Chambers & Lichtenberg (1994) showed that the aggregate pest damage in US agriculture was much lower than previous estimates suggested. Their model points out the important distinction between pesticides as single damage control agents and total damage abatement.

In French cereal production (Carpentier & Weaver, 1997) showed that, if multiple pest occurrence and farmer-to-farmer effects are ignored, pesticide productivity can be overestimated by a factor of three. Finally, Saha *et al.* (1997) using an advanced version of the Lichtenberg & Zilberman model showed that the marginal product of pesticides is about half the magnitude estimated under simplified economic models.

Progress in economic analysis of pest control made clear that previous studies tended to overestimate their productivity effects. The older economic models treated pesticides as direct productive inputs instead of recognising their true nature as one among several damage abatement factors. Overwhelmingly, the recent theoretical, normative, and causal empirical studies concerning pesticide use show that pesticides are overused. Of course this should not lead to the conclusion that pesticides are no longer needed, but compared to their inaugural phase, we now know that society would be much better off if world agriculture would use less rather than more pesticides.

Lesson 4

Methodological flaws were underlying major studies of crop protection scientists mainly concerned with crop loss studies. For example, the study by Oerke *et al.* (1994) on global crop loss due to pests compares crop yields of treated versus untreated plots thus assuming that there is no other alternative than either using synthetic pesticides or leaving them aside. Most data were taken from small plot experiments in a treated environment, where natural pest control had been eliminated inadvertently. Unfortunately, the results of both older economic studies and crop loss assessments by crop protection scientists created an information environment which made decision makers to believe that the economic benefits of pesticides are beyond doubt and that further benefit assessment is not necessary. Due to the pivotal role played by the pesticides industry (Tombs, 1993) a 'political economy' was created where the information environment made it difficult to reach decisions based on objectively verifiable information.

The consequence of distorted information is that the regard given to alternatives diminishes. Those groups who benefit from pesticides tend to monopolise information, influence other groups such as research and extension and thus generate a disincentive for the development of non-chemical alternatives. The relatively small proportion devoted to biological control in private plant protection research and the 'rhetorical embrace' of concepts such as Sustainable Agriculture and Integrated Pest Management by the chemical industry illustrates the situation.

Lesson 5

The fifth lesson to be drawn by looking at the past fifty years of synthetic pesticide use in world agriculture is that a self-reinforcing process became initiated. Farmers, in designing their cropping plans assume the continuous availability of pesticides. They have facilitated a reduction of self-regulating mechanisms in their production system and thus artificially increased the profitability of pesticides. This process made farmers dependent on pesticides adding a real world example to the phenomena of path dependence studied by economists (Cowan & Gunby, 1996). Dependence reduces options available to farmers. Ongoing substitution of internal regulation mechanisms within a farming system by external inputs, stimulated by the assumed availability of chemical solutions, often annihilated the knowledge on alternatives.

A comparison of the experience from synthetic pesticides with the issues arising from the transgenic technology suggests some similarities. Therefore, a framework for assessing the introduction of GMPs in agriculture should be based on high scientific standards and should make provisions that avoid a repetition of the costs caused by synthetic chemicals.

A comparison between pesticides and GMPs

Historical developments

Natural substances have been used as pesticides for centuries (Orlob, 1964). The famous Salvarsan, an organo-arsenic compound, was invented in 1907 (Ehrlich, 1909). It induced the development of organic mercury compounds, which became extremely successful as seed disinfectants. The use of organic compounds in crop protection was preluded in human medicine by the advent of antibiotics and sulfa preparations in the 1930s. The breakthrough of organic pesticides came with DDT, widely applied during World War II for control of malaria and typhus. After World War II substances such as DDT, DD, 2,4-D and carbendazim showed the promise of pesticides. A century of scientific development led to the present-day situation.

Genetic modification roots in the famous Watson & Crick (1953) model of DNA. Once DNA was identified as the carrier of genetic information, modification of DNA came in sight. Bacteria were genetically modified in 1977 (Itakura *et al.*, 1977) and plants in 1982 (Meeusen, 1996). The challenge of genetic modification was foremost the intellectual satisfaction of acquiring new insight in the workings of nature, but commercial interests arose simultaneously. The first transgenic plant was marketed in 1994, the Flavr Savr™ tomato (Kridl & Shewmaker, 1996). Many other GMPs followed, some with improved storage or processing quality and others with resistance to insects, viruses or herbicides.

Ethical implications

After World War II organic pesticides were applauded as instruments saving the world from disease and hunger (see quotation) and freeing the farmer from slavenly toil. Such expectations have come true to a large degree. Industrialisation in the West was stimulated by impressive improvements in labour productivity in agriculture, in the pesticides area primarily due to herbicides (Hetsen & Hidding, 1991). The optimism was such that the large-scale consequences of the application of thousands of tonnes of poisonous material were not seen or at least were ignored. The counter-movements starting the opposition against the use of pesticides had practical and ethical roots (Carson, 1962). Entomologists saw the self-defeating effects of pesticides to control insect pests (*vide* Van Den Bosch, 1978) and naturalists noticed destructive effects on wildlife (e.g. Hunt & Bischoff, 1960; Koeman, 1972).

Genetic modification, in contrast, was accompanied by ethical reflection from the beginning (Watson & Tooze, 1981). An open letter in Science (Singer & Soll, 1973) initiated the discussion in the USA, which culminated in the famous Berg letter of 26 July 1974 (Berg *et al.*, 1974). The letter led to a one-year moratorium voluntarily accepted by the scientists involved, a novelty in the natural sciences. Even industry participated in the moratorium. Deliberations during that moratorium led to regulatory oversight by the US Government. The second Asilomar Conference (1975, USA) discussed a.o. legal liability and introduced the concept of 'biological containment'. In Europe, concerns on genetic modification technology (GMT) were discussed i.a. during an international congress (Federation of European Biochemistry Societies) in Amsterdam, 1972 (Schellekens, 1993). In 1974, Dutch scientists ('League of Scientific Workers') discussed the ethical implications of the new technology and the Royal Netherlands Academy of Sciences installed a committee to oversee genetic modification activities in the Netherlands. The committee, which still exists under the name COGEM (Committee on Genetic Modification), received its legal basis in 1990 (Anonymous, 1990a). Ever since the events in the 1970s, ethical reflexion accompanies genetic modification (Van Dommelen, 1996).

Regulatory procedures

Regulatory oversight of pesticides originated from a concern about poor practices in the trade of pesticides and application equipment. The Federal Insecticides and Fungicides Act of 1910 in the USA intended to protect the farmers from swindle by a rapidly emerging pesticides trade. Protection of agriculture was the explicit objective of the Dutch Pesticides Act of 1962. When the undesirable side effects became a subject of public concern, measures to protect the consumer, the environment and the agricultural worker (about that order) became gradually incorporated into the national Pesticides Acts. European regulation, especially Directive 91/414, overruled the various Pesticides Acts in the Europe Union and established a strict regime which is slowly effectuated. The German Plant Protection Act of 1986 went one step further by imposing Integrated Pest Management (IPM), but that obligation of the farmers could not be enforced.

In contrast to pesticides, again, Genetically Modified Organisms (GMOs) were subjected to regulation from the very beginning (Cantley, 1995). The objective of the regulatory oversight was not to protect agriculture from malafide practices and useless products but to protect man and his environment. Consumer protection came later, at least in the EU, where a three-tiered system was installed. The first tier regulates the deliberate introduction of GMOs into the environment (Anonymous, 1990b), where environment is the major concern and worker health a minor one. The second tier is the usual registration of the variety, here the genetically modified variety, for commercialisation, where agriculture is the major concern (*vide* Anonymous, 1970). The third tier is the permit to commercialise a GMP or its product as food or feed, with due labelling, where consumer protection is the foremost concern (Anonymous, 1997a; Regulation EC 258/97).

Commercialisation

The early, inorganic pesticides were sold by small traders and the application equipment was made by local blacksmiths. Small companies merged into large, research-based chemical companies after World War I, e.g. 'IG Farben Industrie' in Germany and 'Imperial Chemical Industries' in England and these tended to monopolise the market. Organic mercury compounds for seed disinfection were a major product. After World War II, a fierce competition arose among a large number of chemical companies, scattered over the Western world, who developed rapidly into internationals. Research costs could be earned only when a successful compound was sold world-wide for use on a few major crops. Even the poorest and remotest farmer was eventually reached by salesmen and persuaded to apply pesticides, world-wide. The Green Revolution technology, introduced in the developing world after 1960, was a 'blessing' for the chemical companies since the early high-yielding varieties could hardly survive without pesticide cover. The pesticides industry responded to rising regulatory costs and environmental constraints with a sequence of mergers which around 2000 seems to come to a stand-still, leaving less than 10 research-based pesticide companies. Meanwhile, many patents expire. Off-patent products, so-called generics, produced by various new companies, primarily in Asia, form a new threat to man and the environment (Oudejans, 1999).

After several mergers the relatively many pesticide companies turned into relatively few bioscience companies, some investing nearly exclusively in GMPs. Their marketing is highly aggressive but their products are, from a molecular point of view, rather primitive. The first GMPs contain simple, rough-and-ready constructs for herbicide resistance and/or specific insect resistances. Rapid return on investment is the drive. Newer and better products may be introduced later with benefits not only for the bioscience companies and farmers in affluent countries, but also for the consumers and for the large body of farmers in developing countries.The large companies with their monopolizing tendencies are surrounded by a suite of university departments and small biotech companies with a wealth of advanced ideas. The lifescience industries are aware of the many objections against the first generation of GMPs and try to meet these objections with improved GMPs (Hansen & Wright, 1999).

Biological effects: pesticides outside and inside plants

Pesticides are applied to plants from the outside. Systemic pesticides penetrate the plants to kill the pest organisms from within. Some substances, legally considered as pesticides, only strengthen the plants or enhance their natural resistance.

Most plants are naturally resistant to most pests. Resistance is a complex phenomenon in which chemical substances play a dominant role (e.g. Van Genderen *et al.*, 1996). These substances may be poisons (also for humans), antifeedants, repellents, or signalling substances. In the latter case, plants may respond with programmed cell death (apoptosis), as in the hypersensitivity reaction to fungal parasites. Whereas most pests are kept off by plants, some pests co-evolved with their host plants, overcame their defense mechanisms and became specific pests, often with great economic consequences. For commercial purposes, man sometimes helped the pest by eliminating a natural pesticide through classical breeding procedures. Elimination of gossypol from present-day cotton is an example; it made cotton much more pest-sensitive (e.g. Hedin *et al.*, 1983).

Classical resistance breeding rearranges genes by hybridisation and selects suitable gene combinations from the offspring. The process is steered by combining parents with interesting characteristics in the hope that at least one genotype in the offspring will have the desired combination of traits. The genes themselves are unknown. In resistance breeding by genetic modification, a specific and completely characterised gene from whatever source (e.g. plant, animal or bacterium) is introduced into an agronomically acceptable plant in order to confer a specific 'trait' to that plant. The trait can be an ecological adaptation, a change in processing or consumer quality, or – in our case – resistance and/or tolerance. Pest resistance usually is highly specific for the target pest and herbicide tolerance is highly specific for the chosen herbicide. Classical breeding and genetic modification may produce phenotypically identical 'traits' that genotypically are very different indeed.

The end result may be that a 'transgene', a gene artificially introduced in a new host, conditions the production of a pesticide in the plant, a non-original or non-native pesticide. Such is the case with *Bt*-resistance against insects in e.g. maize. *Bt* refers to the bacterium *Bacillus thuringiensis*, a common soil organism, which is industrially produced as a biopesticide against various insect pests. The bacterium contains one or more toxins highly specific to selected insect pest species. The external effect of classical *Bt* was made into an internal effect by GMT. This internal effect is indicated by the term 'pesticidal plant', a misnomer because all plants contain pesticidal substances; the new legal term for the internalized effect will probably be 'plant expressed protectant' (APS e-mail service).

Biological effects: pollution

Less than 5 percent of the applied pesticide arrives at the target, the pest organism to be killed (Pimentel & Levitan, 1986). Over 95 percent of the pesticide enters the environment as a pollutant. Nearby pollution of soil and surface water is most obvious. The deeper soil water and therewith the drinking water sources become polluted, and pesticides are spread through run-off rain water and transported over long distances. Pesticides evaporate and are carried by the wind to far-away targets. Effects of pesticides on human health are well documented and include pesticide-induced disability, disease, death or sterility in humans (e.g. Loevinsohn, 1987; Kishi *et al.*, 1995; Pimentel *et al.*, 1980, 1991).

Plants with chemical resistance, of natural or GMT origin, hardly produce pollution though various external effects of plants are known such as allelopathy (Putnam & Duke, 1978), where excreta from plants restrict growth of other plants. Similarly, transgenic *Bt*-resistant plants may excrete their toxin into the soil (Saxena *et al.*, 1999). Eventual consequences are under debate. Wind-borne pollen from *Bt*-plants may be deposited on non-crop plants and endanger non-target insects (Losey *et al.*, 1999).

Biological effects: food chain

Food chain effects by bioaccumulation are frequent. Predators at the end of a food chain, such as birds of prey and seals, may take in so much pesticide that their survival and reproduction are seriously impaired. Inversely, the well-being of such end-of-chain animals signals the health of the ecosystem.

Man is also an end-of-chain animal. Unusual morbidity, complete sterility, impaired fertility (possibly also sex ratio changes; De Cock, 1995) and mortality can be signs of pesticide poisoning. But pesticides may have more insidious effects. They may be cancerogenic, teratogenic or mutagenic. At very low but constant dosages they may affect the nervous, immune, or reproductive system. Intergenerational effects cannot be excluded.

With GMPs the present debate concentrates on the food chain (Zadoks, 1999). The industry's numerous though small-scale field experiments do not indicate a problem, but problems do appear in experiments specifically designed to the purpose. Unfortunately, some published experiments (Hilbeck *et al.*, 1998) on lacewing larvae dying on a diet of *Bt*-maize fed caterpillars were poorly designed and cannnot be considered representative. The numbers of predators (Pilcher *et al.*, 1997) and parasitoids on GMPs need not but may be lower than on unsprayed non-GMP crops but in the vegetations surrounding the GMP crops the beneficials will not be disturbed by pesticides out of target. Potatoes made resistant to the larvae of the Colorado beetle killed these larvae but not the aphids feeding on the potatoes. However, part of the coccinellids predating these aphids died (Birch *et al.*, 1996). Pollinators might be damaged if pollen contains *Bt* poison, but this fear seems unwarranted (Arpaia, 1996). The impression is gained that a transgenic toxin specific for phytophagous insect species of one order might damage non-target species of the same but not of other orders.

Biological effects: pest and plant population changes

Pesticides may cause population changes in two ways. First, the target pest population, which is decimated but not eliminated, may become tolerant to the pesticide; hundreds of 'pesticide tolerance' cases are on record (De Waard, 1993). Second, the elimination of beneficials by pesticides may give another pest species the opportunity to explode and become a 'secondary pest', another frequent event (Kenmore, 1996; van den Bosch, 1978).

Resistant varieties produced by classical breeding methods may be attacked by new strains of the pest against which the resistance does not work. Such strains appear naturally by mutation and recombination of genes. Thousands of such events are on record over the last 80 years, for wheat, potatoes and scores of other crops. Similarly, transgenic resistance may be 'broken'. Genes for *Bt* tolerance have already been found in target pest populations (Gould *et al.*, 1997). As with classical breeding for monogenic resistance (Zadoks, 1993), new genes will be kept in store. Loss of hostplant resistance through the appearance of new pest genotypes is a cost to users and also to non-users of the technology when other farmers become affected too. New regulatory measures intend to reduce the risk of pest tolerance by prescribing co-cultivation of non-transgenic crops (Anonymous, 1998a,b). Farm level costs of these regulations may be considerable.

Some crops are typical cross-pollinators and most self-pollinating crops have at least some degree of cross-pollination. Undesirable out-crossing to non-modified crops may occur. Pollen may fertilise wild or feral species and thus cause population changes. This out-crossing (of non-modified crops) is as old as agriculture and it seldom led to problematic situations. The Swiss case, where the wild tetraploid (but not the diploid) population of *Medicago falcata* was nearly entirely replaced by the tetraploid agricultural type *Medicago sativa* (alfalfa) is as dramatic as it is exceptional (Rufener-AlMazyad & Ammann, 1999).

Transgenic crops will cross out and incidentally or regularly pollinate wild relatives (Lutman, 1999). Transgenes for resistance may introgress into populations of wild species. If transgenes for herbicide resistance enter wild plant populations where no herbicides are used, these genes will not confer a selective advantage. In contrast, transgenes for pest resistance may give a selective advantage to their plant hosts if these hosts are threatened by the respective pest. At best, the transgenes provide an extra protection in addition to the various levels of natural resistance. The possibility of population shifts in wild vegetations after introgression of transgenes cannot be excluded (Schouten, 1998).

Economic assessment of genetic modification technology (GMT)

A welfare theory approach

Assessing the economic benefits of public or private investments in transgenic crops requires to compare the sum of expected discounted benefits with that of known and expected discounted costs. The comparison is, unfortunately, not so straightforward as it may appear at first glance. Aside from specifying an appropriate economic model by taking into account economy-wide effects of GMPs and considering their equity implications (Quaim & Von Braun, 1998) in contrast to limiting the analysis to a partial model of the agricultural sector, the application of cost benefit analysis of GMPs is constrained by other difficulties. Among these are that, as for synthetic pesticides, negative externalities can result from transgenic crops. Therefore, regulatory agencies decide upon their release into the environment after risk assessment. A group of experts referring to the latest state of knowledge is requested to decide on behalf of society how much risk is acceptable. The assumption is that, when the technology has been approved, the user will follow the rules and regulations as designed by the regulatory agency. These rules are supposed to ensure bio-safety in accordance with the assumptions underlying the experts' decisions. Thus, the regulatory decision contributes to the total costs of the technology, provided that the technology users abide by the rules. In case of deviations from the rules, as happens frequently with pesticides in Germany (Fleischer, 1998), the costs to society are higher.

Total costs of pesticide and GMP technologies are composed of the development costs, in the case of pesticides strongly influenced by regulatory requirements, the production and marketing costs, the application costs and finally the external costs, the inevitable ones and those arising from inappropriate use, incidental misuse or unexpected accidents. It is safe to assume that the development costs of a synthetic pesticide under the present registration requirements are higher than those of GMPs. However, as new risks associated with GMPs are recognized by scientists or perceived by the public, regulatory requirements will be tightened.

In the USA, benefit assessment of new technology (here pesticides) is applied following simplified economic models that may lead to conflicts on registration which require court decisions (Fagin & Lavelle, 1996). Benefit assessment, following the principles of economic welfare theory, is not applied by the European regulatory agencies. Usually, benefit is defined as the biological adavantage of the technology to be registered. In the case of pesticides the commercial product to be registered should be more effective than existing products or fill a gap where no chemical control method existed. In the case of crop varieties a new variety needs to have some advantage over existing ones in one or more important traits such as yield, harvestability or pest resistance. A biological advantage does not necessarily correspond with an economic benefit. The latter depends on the potential of the new technology to increase farmer profit and to augment net benefit to society which economists measure as the sum of producer and consumer surplus.

Appropriate benefit assessment of GMPs is possible only if their impact on the productivity of the agricultural sector is captured. This requires economic models that allow for measuring technology adjustments at least in the agricultural sector but to be more accurate they should also take into account forward and backward linkages to other sectors of the economy. The benefit is then to be measured as the increase in productivity which is equivalent to the reduction of food production costs for a given level of aggregate food demand.

Since in most industrial countries agricultural markets are distorted by policy intervention, the market price does not indicate the true marginal costs of resources. Hence the true price of resources (shadow price) must be determined (Marggraf & Streb, 1997). This requires that benefit assessment of transgenic crops is carried out in the context of an open economy framework, i.e. valuing the additional production gained or the resources saved at world market prices. When GMPs affect the production of a commodity in a country, and the ensuing change in domestic production does not lead to a change in the world market price of that commodity, the benefit of the introduction of GMTs only occurs at the supply side.

The effects of the new technology can then be measured in terms of a shift of the supply curve (area OAB in Figure 3), equivalent to an additional rent to the producers. For most of the current generation of GMPs this is exactly what is happening, i.e. benefits go to producers and input suppliers and rarely to consumers. However, the model presented in Figure 3 will have to be changed if GMPs will affect the production of a commodity for which the change in supply may indeed lead to a change in the world market price, or if product quality is affected (improved). In these cases the new technology will also generate benefits to consumers either through lower prices or increased 'willingness to pay' for improved quality.

For the time being, the benefits of transgenic crops occur on the producer side only, though it is not clear how much goes to the farmers and how much is captured by the supply industry. Consumers show growing resistance to food produced from transgenic crops (certainly in Europe and increasingly in the USA) although they readily accept biotechnology in human health. As pointed out by The Economist (June 19th 1999): *'Why is it different when biotech is applied to agriculture? The answer is that the clearest gains from the current crop of GM [genetically modified] plants go not to consumers but to producers. Indeed that was what their developers*

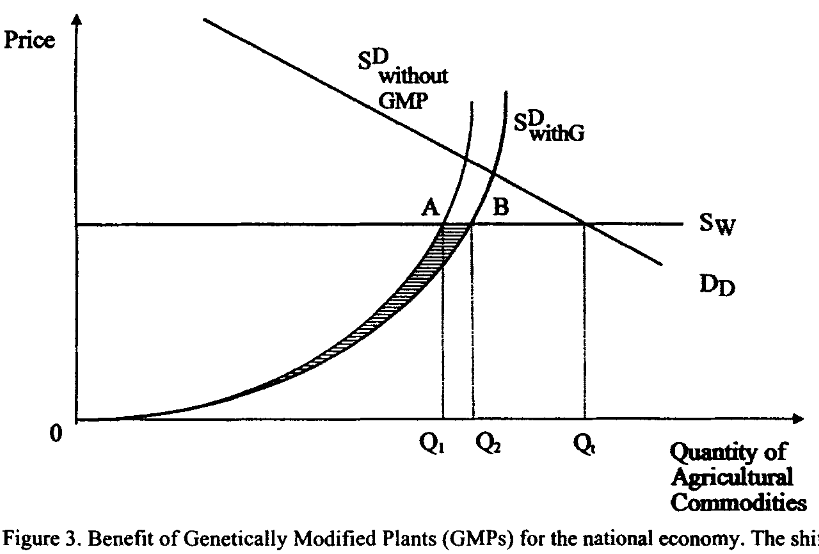

Figure 3. Benefit of Genetically Modified Plants (GMPs) for the national economy. The shift in the supply curve indicates the cost advantage of GMPs to the agricultural sector (indicated by the shaded area OAB) under the assumption that domestic supply does not affect the commodity price on the world market.

intended: an appeal to farmers offered the purveyors of GM crops the best hope of a speedy return. For consumers, especially in the rich world, the benefits of super-yielding soybeans are less clear: the world by and large has too much food in its stores; developing countries principally lack money not food as such.'

Assessing the economic role of modern biotechnology in crop protection cannot draw from a rich source of empirical case studies. Evidently the first generation of GMPs, with herbicide resistance, spread quickly in soybean and maize in the US. However, there are indications that the introduction of crops resistant to herbicides has not always resulted in lower costs of weed control (Benbrook, 1999). Given the lack of data an empirical assessment of the costs and benefits of GMT cannot yet be provided. However, further conclusions can be derived by working with assumptions based on ecological and economic principles and drawing upon the experience with pesticide-based technologies. Three major issues have to be resolved as a precondition for the conduct of a meaningful cost benefit analysis for GMTs:

(a) Identification of a reference system.
(b) Identification and quantification of the costs, and
(c) Identification and quantification of the benefits.

The reference system

The current, first generation of transgenic crops is highly biased toward crop protection, i.e. herbicide and pest resistance. Much of the experimentation and most of the commercial use has been in these two categories (Ollinger & Pope, 1995). Unless synthetic pesticides are ineffective in preventing crop losses, transgenic crops will not increase yield but reduce costs at best. Initial expectations of increased crop yields as a result of the introduction of transgenes that confer pest resistance could not be met (Ruttan, 1999), e.g. yield reductions in GMPs have been recorded repeatedly (Forrester & Pyke, 1997; Fox, 1997; Song, 1999).

Currently, transgenic crops provide the option that either the use of synthetic pesticides can be substantially reduced or, in the case of herbicides, that their application can be better timed and targeted. By and large, transgenic varieties (as classical resistant varieties) allow the substitution of one damage control method by another although there may be complementary relationships with other variable inputs (Just & Hueth, 1993). Thus the relative advantage of these varieties depends on the prices of their substitutes and complements. At the farm level the impact of transgenic varieties is measured rather simply by comparing the net revenues of the current practice with those after adopting transgenic seeds. At the aggregate level, i.e. from the viewpoint of the public in general, the question of a meaningful reference system is less trivial because several alternative crop protection strategies exist. The available options can be broadly grouped as Chemical Crop Protection (CCP), Threshold IPM (TIPM), Ecotechnology (ET) and Organic Farming (OF). The difficulty arises because GMT can be combined with all strategies, though present OF explicitly excludes GMPs.

In *Chemical Crop Protection* (CCP) farmers rely on pesticides as a major crop protection tool. To date, CCP is still the dominating strategy. Indirect measures of control (e.g. crop rotation) are applied only if clear agronomic benefits demand their use. High costs of labor and lack of knowledge impede the use of systematic pest monitoring, which remains an exception. For example, a study carried out in Northern Germany on farmers' integrated farming practices (Lütke-Entrup & Hensche, 1995) revealed that only about 8 % of the farmers follow what could be called integrated farming practices, even according to loose criteria.

Threshold IPM (TIPM) is based on the concept that farmers follow scientifically established critical pest levels as the basis of chemical control. The threshold concept dates back to Stern *et al.* (1959) who first defined the economic injury and economic damage levels (*vide* Zadoks, 1985). A vast amount of literature in plant protection (not referenced here) and in economics (e.g. Headley, 1972; Norton, 1976) deals with questions of definition and modelling of threshold levels. Gradually it became clear that an IPM, based on experimentally defined critical pest levels, was embraced by chemical companies as their version of IPM, with thresholds specifically defined for their chemical products (Zadoks, 1994). Threshold IMP forms the core of industry promoted Integrated Crop Production (Anonymous, 1997b). Unfortunately, no empirical evidence is available on the adoption of this concept in practice. Nevertheless TIMP (under the heading Integrated Crop Production) is the official government policy in crop protection of some countries, e.g. in Germany (AgrarEurope 06/1998).

A third reference system we call *Ecotechnology* (ET). We summarize under this term all approaches to Integrated Pest Management (IPM) which are based on farmers understanding the ecosystem interactions rather than simply following extension recommendations. ET contrasts the top-down, technology-driven approach emphasised in CPP and TIPM by focussing on a philosophy of people's participation. In Europe, attempts have been made in The Netherlands with farmer groups (Wijnands & Vereijken, 1992) and in Germany with on-farm research in university farms (Gerowitt & Wildenhayn, 1997). In developing countries this approach has reached wide recognition especially through the FAO Inter-country Programme on IPM in Rice (Kenmore, 1996). Unlike in Europe, farmer participatory IPM, learned in Farmer Field Schools, is actually practiced by farmers in the field (Vos, 1998). An important observation that resulted from the field implementation of such projects is that pesticide use could be substantially reduced. Unlike OF, Ecotechnology does not exclude GMPs but would prefer to handle things differently. In addition to the necessary expert opinion it would wish to gain transparancy by public discourse (*vide* Von Schomberg, 1999). This would include the conduct of cost benefit analysis and the symmetric participation of consumers and other civil society groups on the one hand, and farmers and industry on the other hand.

A fourth reference system is *Organic Farming* (OF), legally defined by EU regulation 2092/91. It is the 'ultimate' basis of comparison for GMPs because it categorically excludes synthetic pesticides and fertilisers, and has announced to exclude GMPs. In the EU, the area under organic farming has roughly doubled between 1993 and 1997 to reach about 2.2 million ha. By 2010 a share of 15 to 25 % of the agricultural land has been forecasted (AgrarEurope 22/99).

With regard to defining a reference system for measuring the economic impact of

GMPs the possibility to reduce the application of synthetic pesticides with the available systems is important because this reduction is claimed to be a major benefit of the current generation of transgenic varieties. It is misleading if dramatic savings in insecticides are claimed to be the success of *Bt*-cotton varieties when the existing cotton pest management is highly inefficient. A static comparison of the benefit stream of GMPs with that of CCP would lead to an overestimation of the benefits of GMPs. An example for such misguided calculations was given for transgenic *Bt*-crops (Whalon & Norris, 1997). A rate of return of 2:1 (which is not dramatic comparing the rate of return that could be shown e.g. for biological control in Africa (Herren, 1998)) was calculated if *Bt*-crops capture a 1 % share of the global insecticide market assuming that *Bt*-crops are the only means to reduce social costs of insecticide use. A realistic comparison implies, however, that the nex best alternative, i.e. an optimised current system, is used as a reference.

Identification and quantification of costs

To estimate the costs of transgenic varieties their pricing mechanism needs to be understood. At a first glance the costs of GMPs are similar to those of synthetic pesticides. These include the costs of development, reproduction and distribution of transgenic products and the costs due to biosafety regulations. Matters become complicated because in modern biotechnology the Intellectual Property Rights (IPR) are probably the crucial cost component but so far no well-founded pricing model exists. Zilberman *et al.* (1999) made a distinction between two types of products, (1) components of knowledge about genes or processes necessary to produce biotechnology products such as varieties, and (2) resulting marketable products, i.e. the transgenic varieties whose production depends on (1). While marketable products may follow the concept of the near-perfect market model with a positively sloped supply curve this model may not be applicable for (1). The reason is that the market for knowledge components is likely to be monopolistic. This can lead to a socially suboptimal supply of technology components and thus of marketable products.

In addition, transgenic varieties may produce negative externalities through environmental and health risks (see above). Here, matters are complicated by the impossibility to estimate such costs at present because the existing level of science does not yet allow to determine their full impact. As yet, we cannot assess the probability of undesirable events. Thus the full costs of GMPs cannot be captured by standard risk analysis. Then, the regulatory costs and the costs of monitoring and of precautionary measures only are a minimum proxy for the full costs of GMPs. As the history of pesticide regulation has shown costs will rise as more evidence on externalities becomes available.

Benefit assessment

The nature of the current GMP technology demands that the same principles as used in measuring pesticide productivity be applied. The correct methodology is to apply a damage abatement framework (Lichtenberg & Zilberman, 1986). This means that pest-resistant traits in transgenic varieties must be treated as damage control agents and not as yield increasing inputs. After all, the use of *Bt*-genes is like making a pesticide inside the plant instead of placing it there indirectly as with systemic pesticides. In addition to the damage abatement framework the analysis of pesticide productivity (Waibel *et al.*, 1999) indicates that three other factors are to be considered in the benefit assessment of transgenic varieties.

First, benefit assessment must recognize the possibility that a large scale introduction of GMPs into farmers' fields can make the environment to react, e.g. by developing new biotypes that overcome the resistance (see above). A strong decrease of an insect pest population due to varietal resistance may lead to dangerously low population levels of beneficials. Therefore, a dynamic framework is required that takes into account the state of the natural resources such as pest susceptibility and beneficial organisms. If new pest outbreaks are induced, what is originally measured as a benefit of the resistance transgenes may turn into an externality to be measured as a loss in natural resource stocks.

Second, we need to examine whether transgenic varieties do indeed possess risk-reducing properties which could be added to their productivity-enhancing benefits. In the case of pesticides, recent analysis (Pannell, 1991; Regev *et al.*, 1997) has shown that the earlier connotation of pesticides as risk-reducing agents (Feder, 1979) cannot be maintained. Adding a risk-premium to the technology fee for transgenic cultivars will be unjustified if the reduction in net revenue variance is traded off for an increased probability of 'disaster'.

Third, the definition of a farmer's utility function in a society dominated by consumerism and mass media may require to go beyond the profit maximisation hypothesis. According to Swinton (1998) environmental and social objectives must be added as variables in the utility function. Hence the marginal costs of transgenic varieties can no longer be equated to their marginal value product but should be corrected by the disutility of image loss if 'things go wrong' and of possible health and environment concerns of the consumer. Image loss and consumer concerns are costs. Here, the change in social environment between the introductions of pesticide and GMP technologies is as important as it is difficult to handle in economic terms.

Taking these theoretical points into account one could speculate on the potential benefits of GMPs in crop protection over time relative to alternative strategies. This is the best one can do in the absence of empirical studies on the adoption of transgenic crops such as might be feasible for maize and soybean in the USA.

In Figure 4 the result of such a speculation is presented. The diagram portrays time on the X-axis and technology adoption (closely related to total benefits) on the Y-axis, as they may develop as a result of the potential of the technology and the expected policy conditions. The intersection with the X-axis represents the turn of the millennium. In interpreting the graph we may assume that each strategy is the result of investment in technology by both the private and the public sector resulting in a benefit stream over time.

Among the major crop protection strategies of today CCP began about 50 years ago. We conclude that its benefit stream may have surpassed its peak and that its use

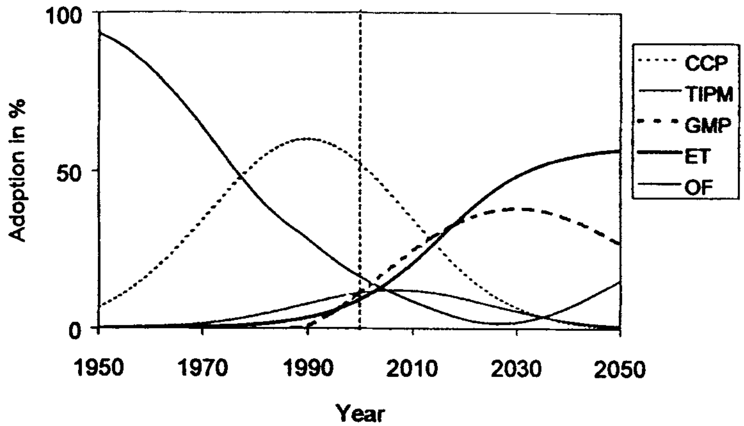

Figure 4. History and future of technology adoption in crop protection. The graph shows the subjective assessment of the authors of past and future adoption of alternative crop protection methods at the global level. Note that the individual adoption rates add up to 100% at any point in time. CCP = Current Crop Protection, TIMP = Threshold IPM (Integrated Pest Management), GMP = Genetitally Modified Plants, ET = Ecotechnology, OF = Organic Farming.

in industrialized countries is likely to decline (Swinton, 1998). Productivity of available chemicals is impaired by the development of resistance and the augmentation of secondary pests. Development of new products is constrained by high development costs and strong competion in the pesticide market.

A similar fate we attribute to Threshold IPM which is seen as a derivative of the 'old' chemical strategy. Unless there is a policy change leading to drastic increases in pesticide prices, accompanied by significant investment in farmers' knowledge, field monitoring will not be conducted in a way that attributes real value to the additional information obtained by monitoring. The private sector so far has not made this investment and it is unlikely to do so because of the in-house competition this would create with pesticide sales. Hence, we have reasons to believe that the 'Integrated Crop Production' rethoric of the chemical companies will turn out to be self-defeating.

GMP as a strategy promoted by the private sector, mostly by the same companies who sell pesticides, has grown rapidly between 1995 and 1998, mainly in the USA. In Europe recent consumer reactions do not indicate a similar trend. The area planted to transgenic crops has grown rapidly during 1997 and 1998 (James, 1998) but its market share still is only a fraction of those from chemical pesticides. The latter is in the order of magnitude of US \$ 32 billion. If the food industry will be able to reduce consumer fears, GMPs might have the potential to significantly substitute synthetic pesticides and result in a moderate adoption of this technology. We placed the adoption curve above the one of OF because of the latter's limitations as a world-wide food production strategy. We nevertheless think that a GMP strategy with implementation largely left to the private sector may not become accepted overwhelmingly and is likely to produce only moderate benefits because, as with synthetic pesticides, private interest in maximising sales revenues will stimulate farmers to use inputs inefficiently and therefore may result in negative externalities.

Among the strategies which we have defined we attribute the highest adoption potential to Ecotechnology (ET), mainly because it is more than just a technology. In our view ET implies a social process that does not rely exclusively on experts' assesments but also on institutionalised dialogues between producers and consumers on the one hand and external suppliers of technology (public and private sector research and extension) on other hand. Such dialogues have a lot to do with changing the way people think about dealing with pest problems. The first step is to substitute 'the language of loss' by 'words of rational choice'. A precondition for success is that national governments but also international organisations show, in addition to moral persuasion, the political will and establish a facilitating incentive structure. We believe that present tendencies in civil society can 'empower' governments to work into this direction.

Conclusions

Two once-new crop protection technologies are compared, chemical technology using synthetic pesticides and genetic modification technology using genetically modified plants (GMPs). Genetic modification of plants for other purposes than crop protection is not considered. Both technologies complement existing non-chemical crop protection methods among which classical resistance breeding.

The two technologies were introduced in different historical, social and political settings. Pesticides were readily accepted and their undesirable side effects were found and reacted upon with great delay. GMPs for crop protection were hailed by some and contested by others from their beginnings.

With the pesticides technology the benefits are privatized whereas a significant part of the costs are externalized and thus borne by society at large. Since a similar tendency is apparent with GMPs, some lessons are drawn from the pesticides story. 1. Negative externalities are not fully known at the time of introduction and tend to increase with the scale of technology adoption. 2. Once negative side-effects become known, regulatory agencies tend to react with increasingly sophisticated regulation; this is likely to increase the costs of GMPs. 3. Like with today's pesticides, benefits of the current generation of GMPs are assumed rather than proven. Due to the methodological difficulties to correctly capture the productivity effect of damage reducing interventions in crop production there is a danger that benefits of current GMPs are overestimated. 4. As in the case of pesticides, GMPs became introduced rapidly and quickly dominated the scientific discussion in agriculture. Accompanied by dramatic structural changes in the agribusiness industry the creation of another path dependence is feared, where valid alternative technologies may become marginalized. An increase of the costs of change over time becomes a likely scenario.

The changes which took place in societal values since the time of introducing pesticides necessitate a different conceptual framework for assessment. Whereas during the 'pesticide period' a technological view dominated society this is no longer true in the 'GMP period'.

An assessment of GMP technology based on welfare theory is necessary. This can be applied where GMPs became introduced on a large scale, as in the USA. Empirical analyses that not only look at the risks but especially at the benefit side are urgently needed in order to rationalise the discussion on GMPs. Most importantly, for the conduct of such studies a reference system is needed which portrays a realistic alternative. In this paper four possible reference systems were described. 1. Chemical Crop Protection (CCP), 2. Integrated Pest Management using Thresholds (TIMP), 3. Ecotechnology (EC) and 4. Organic Farming (OF).

In the absence of empirical studies at this point of time, we can only speculate on the potential adoption and the potential benefits of GMPs over time for crop protection purposes on a generalized, global scale in relation to other crop protection strategies. We conclude that the current strategy of introducing GMPs is unlikely to lead to sustainable adoption while at the same time CCP and its modified version TIMP are likely to decline. Instead, we submit that if GMPs are handled in the context of EC (Ecotechnology), the scale of their introduction will be closer to its socially optimal level.

The authors venture that a welfare theoretical approach, which combines scientific and subjective judgements of civil society in a discursive setting will reduce the costs of introducing GMPs for the benefit of society at large.

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